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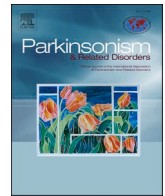
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Short communication

Low-frequency oscillation suppression in dystonia: Implications for adaptive deep brain stimulation

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ABSTRACT

Background: Low-frequency oscillations (LFO) detected in the internal globus pallidus of dystonia patients have been identified as a physiologic marker for adaptive Deep Brain Stimulation (aDBS), since LFO correlate with dystonic symptoms and are rapidly suppressed by continuous DBS (cDBS). However, it is as yet unclear how LFO should be incorporated as feedback for aDBS.

Objectives: to test the acute effects of aDBS, using the amplitude of short-lived LFO-bursts to titrate stimulation, to explore the immediate effects of cDBS on LFO-modulation and dystonic symptoms, and to investigate whether a difference in the resting-state LFO is present between DBS-naïve patients and patients with chronic DBS.

Methods: seven patients were assessed during either DBS-implantation ($n = 2$) or battery replacement surgery ($n = 5$), and pseudorandomized in three conditions: no stimulation, cDBS, and aDBS. Additionally, resting-state LFP-recordings from patients undergoing battery replacement were compared to those obtained during DBS-implantation; LFP-recordings from a previous cohort of six dystonia patients undergoing DBS-implantation were incorporated into this analysis (total $n = 8$ newly implanted patients).

Results: we corroborated that a mild LFO-suppression rapidly occurs during cDBS. However, no acute changes in clinical symptoms were observed after cDBS or aDBS. Remarkably, we observed that resting-state LFO were significantly lower in patients who had been effectively treated with chronic cDBS compared to those of newly implanted patients, even when stimulation was suspended.

Conclusions: our results indicate that LFO-suppression in dystonia, similar to symptom response to cDBS, might be gradual, and remain after stimulation is suspended. Therefore, tracking gradual changes in LFO may be required for aDBS implementation.

1. Introduction

Conventional, continuous deep brain stimulation (cDBS) of the internal globus pallidus (GPi) is an advanced treatment for dystonia. Although cDBS is efficacious, it still has some drawbacks. It takes months to find the right programming settings, as dystonia reacts relatively slowly to stimulation [1]. Also, its clinical benefits can be limited, and stimulation-dependent side-effects, such as parkinsonism and dysarthria [1,2], can occur. In order to minimize the impact of stimulation-induced side-effects, while preserving the beneficial effect

of stimulation, the development of adaptive DBS (aDBS) for dystonia has been proposed [3]. aDBS aims to reduce the total amount of stimulation by titrating stimulation up or down, according to the presence of dystonic symptoms. In order to predict whether symptoms are present, aDBS requires electrophysiological biomarkers (physiomarkers) that are able to reflect the clinical state of the patients [4]. Up to now, the most promising physiologic marker for dystonia is the magnitude of low-frequency oscillations (LFO; 4–12 Hz) embedded in the local field potential (LFP) activity of the GPi. Those oscillations are increased in dystonia [5], and correlate with the severity of dystonic symptoms [4]. However, it is as

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yet unclear how LFO should be incorporated as a feedback signal for aDBS, given that these oscillations present distinctive characteristics at different timescales. On a millisecond timescale, it has been observed that LFO occur in the form of short-lived bursts, and that the amplitude of those bursts is increased in dystonia patients [6]. On a second-to-minute timescale, it has been shown that GPi-LFO power gets swiftly suppressed in dystonia patients during cDBS, predominantly in patients with phasic symptoms [7]. However, it is still unclear whether a fast LFO-suppression is synchronous with a reduction in dystonic symptoms during stimulation. On a longer timescale (minutes to hours or more), it has been observed that slow increments in background LFO-power take place in dystonia patients chronically treated with cDBS, after stimulation is suspended [8]. Those increments in LFO are proportional to the return of dystonic symptoms caused by switching off stimulation, which suggests that not only symptoms, but also LFO are chronically suppressed by cDBS. For the aforementioned reasons, aDBS could be programmed to respond either to dynamic changes in LFO-burst amplitude, to fast changes in LFO-power, or to gradual changes in background LFO-power.

In this study, we explore the effects of delivering stimulation at three different timescales in dystonia patients, in order to generate data-driven hypotheses about the incorporation of LFO as feedback signal in aDBS for dystonia. Firstly, we test the immediate effects of burst-based aDBS, in which the amplitude of LFO-bursts is used as feedback signal to dynamically titrate stimulation. Secondly, we explore the acute effects of cDBS, in order to confirm the presence of a LFO-suppression directly after cDBS, and to investigate the relationship between this suppression and dystonic symptoms. Lastly, we estimate the chronic effects of stimulation on LFO-power, by comparing the recordings of DBS-naïve patients with those of patients with chronic cDBS.

2. Methods

2.1. No-Stimulation, cDBS and aDBS trials

2.1.1. Patients

Seven dystonia patients who underwent either DBS implantation ($n = 2$) or battery replacement surgery ($n = 5$) at the University Medical

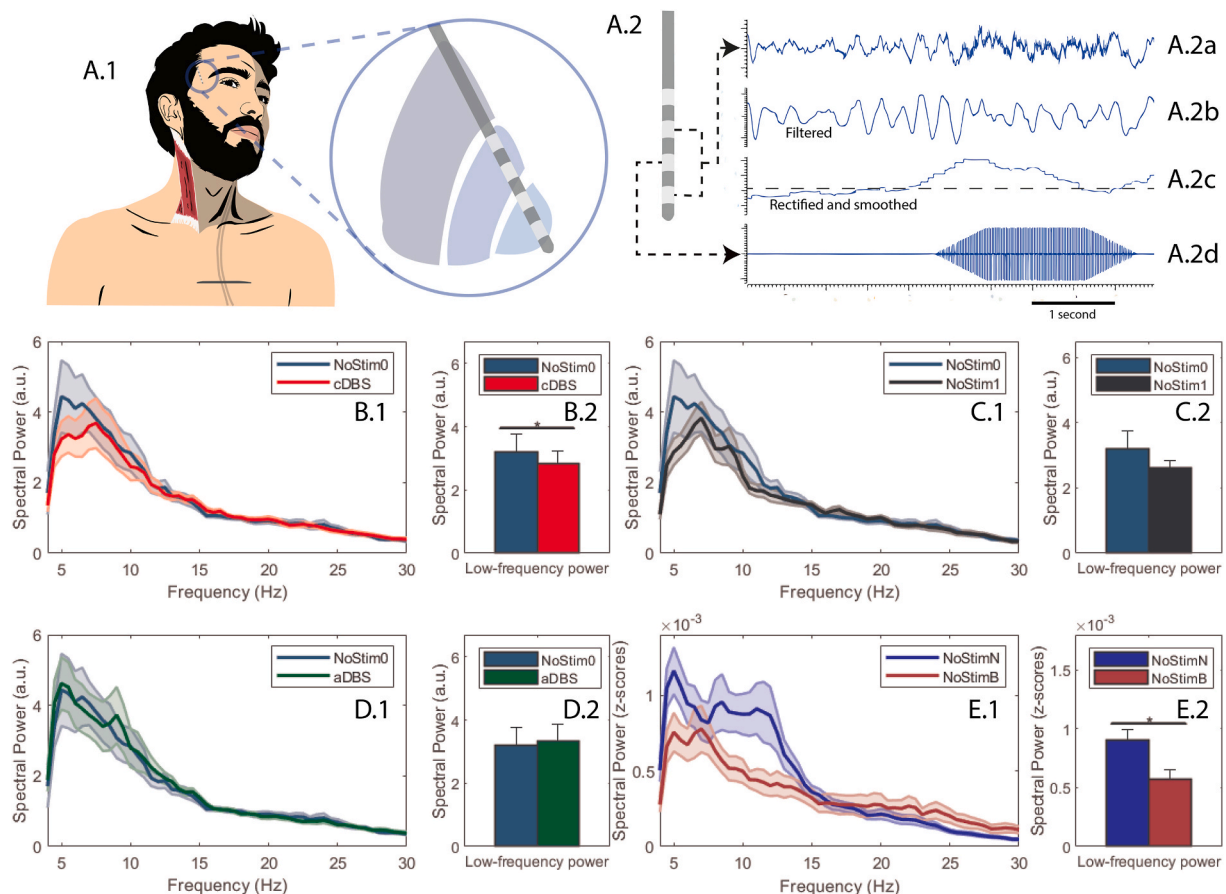


Fig. 1. Characteristics of low-frequency oscillations in dystonia patients across different conditions.

A) Schematic representation of the stimulation paradigm for aDBS: 1. The electrodes implanted in the internal globus pallidus are connected to the external amplifier (not represented here) through externalized extension wires. 2. In this example, recordings are obtained from contacts 0–2, while delivering stimulation from contact 1. a) LFP bandpass filtered at 3–37 Hz. b) LFP filtered around the low-frequency peak (7 Hz in this example). c) LFP is rectified and smoothed, and an arbitrary threshold is set. d) Stimulation is delivered according to the threshold established.

B) 1. Comparison of normalized PSDs obtained from LFP recordings of dystonia patients without stimulation, before pseudo-randomization (NoStim0) and during cDBS. 2. Comparison of mean low-frequency power between NoStim0 and cDBS.

C) 1. Comparison of normalized PSDs obtained from LFP recordings of dystonia patients without stimulation, before and after pseudo-randomization (NoStim0 and NoStim1 conditions). 2. Comparison of mean low-frequency power between NoStim0 and NoStim1.

D) 1. Comparison of normalized PSDs obtained from LFP recordings of dystonia patients without stimulation, before pseudo-randomization (NoStim0) and during aDBS. 2. Comparison of mean low-frequency power between NoStim0 and aDBS.

E) 1. Comparison of normalized PSDs obtained from LFP recordings of dystonia patients undergoing new DBS implantations (NoStimN) and patients undergoing battery replacements (NoStimB). 2. Comparison of mean low-frequency power of patients undergoing new DBS implantations (NoStimN) and battery replacements (NoStimB).

Center Groningen, the Netherlands, were included in the study. The protocol was approved by the local ethical committee; all patients provided written informed consent. Patients were operated under local anesthesia, and anti-dystonic medication was suspended at least 12 h before the procedure.

2.1.2. Recordings

LFP-recordings were obtained 20–30 min after intraoperative stimulation testing (DBS-implantation) or 20–30 min after DBS was turned off (battery replacement). The recording procedure lasted approximately 15 min, which has been previously described [6]. In brief, the extension wires that connect to the DBS leads were exposed and attached to a custom-made amplifier (Fig. 1A). This amplifier allows for bilateral LFP-recordings, using a bipolar montage from either contacts 0–2 or 1–3, and can simultaneously provide stimulation from either contacts 1 or 2, respectively. Bipolar recordings were obtained at a sampling rate of 2000 Hz, while applying a bandpass filter between 3 and 37 Hz.

Spike2 software (V.8, Cambridge, United Kingdom) was employed for the recordings. For each hemisphere, a baseline recording of approximately one minute was obtained from each bipolar contact (NoStim0) during rest, and periodograms were calculated for each bipolar LFP, in order to identify a low-frequency peak. The contacts selected to further record/stimulate for each hemisphere were chosen based on the contacts that met the most of these conditions: a) contacts that presented the highest low-frequency peak; b) contacts that provided a clear LFP signal; c) contacts that were used in the clinical care (in patients with chronic DBS).

After selecting the contacts, patients were pseudo-randomized into three balanced conditions: no stimulation (NoStim1), cDBS, and aDBS. Conditions were measured sequentially in a crossover fashion and lasted around two to four minutes each. During aDBS, LFPs were filtered around the frequency of the highest low-frequency peak (± 3 Hz), and the filtered signal was rectified. A threshold for stimulation was set at roughly 50% of the maximum amplitude of the smoothed-rectified LFP-envelope (Fig. 1 A.2). Similar settings were applied during cDBS and aDBS conditions (frequency 135 Hz, pulse width 60 μ s). The applied amplitude was the maximum voltage tolerated that did not corrupt the recordings and/or that approached the voltage used for cDBS in the clinical practice. In five of the seven patients, a short version of the Burke-Fahn-Marsden Dystonia Rating Scale (BFMDRS) and/or the Toronto Western Spasmodic Torticollis Rating Scale (TWSTRS) was video-recorded during each condition, using the facial and cervical sub-domains. Afterwards, the aDBS amplifier was disconnected and the surgical procedure continued as usual. Videos were blindly assessed by an independent expert in movement disorders.

2.1.3. Signal processing

Selected LFPs were processed offline using a custom-made script in MATLAB (ver. 2018b, Natick MA, USA), and the FieldTrip-toolbox (University Nijmegen, The Netherlands [9]). Bipolar recordings were filtered at 4–35 Hz. Segments of approximately 2 min were chosen from each condition. Jump artefacts were attenuated using a wavelet denoise filter, and contamination occurring at subharmonic frequencies of stimulation or line noise was removed using the DBSFILT-toolbox, by interpolation with neighboring frequencies (Université Lyon, France [10]).

Immediate changes in LFO-power were explored by obtaining periodograms for each LFP in the NoStim0, NoStim1, cDBS and aDBS conditions, using a multitaper window with ± 0.5 Hz smoothing and 0.5 Hz resolution. Each periodogram was normalized by dividing it by the root mean square (RMS) of its total beta power (13–30 Hz), in order to attenuate changes in noise floor due to stimulation, while allowing variations in LFO among conditions. By using the RMS of the beta power, we considered shifts in the whole beta spectrum as a consequence of stimulation changes in the noise floor, and changes in frequency peaks as a result of physiological effects of stimulation (Supplementary Figure

1). Mean low-frequency power was obtained from each periodogram.

2.2. New-implantation and battery-replacement recordings

LFP-recordings during the NoStim0 condition obtained from patients undergoing battery replacement ($n = 5$) were compared to those measured during DBS-implantation ($n = 2$). To complement the DBS-implantation cohort, LFP-recordings from a previous cohort of six dystonia patients obtained during DBS-implantation (described in Ref. [6]) were incorporated into the analysis (total $n = 8$). Previous recordings were re-referenced from monopolar to bipolar, using the configuration 0–2 or 1–3. Channels per hemisphere were selected based on those used for stimulation in clinical practice. LFPs were normalized across subjects by transforming their amplitude into z-scores. Periodograms were derived from those LFPs, and their mean low-frequency power was calculated.

2.3. Statistical analysis

A repeated-measures ANOVA was performed using the mean low-frequency power calculated for the NoStim0, NoStim1, cDBS and aDBS conditions. Additionally, due to the exploratory nature of this study and the limited power of our pilot sample to detect differences at a group comparison level, additional pairwise comparisons were performed between conditions using permutation dependent t-tests. Mean low-frequency power between new-implantation and battery-replacement patients was compared using permutation independent t-tests. BFMDRS and TWSTRS scores were compared among conditions using repeated-measures ANOVA and additional explorative pairwise dependent t-tests between conditions were performed. All units are reported in means \pm standard error of the mean (SEM).

3. Results

Patient information is presented in Table 1. Two GPI-LFP-recordings, each from a different patient, were discarded due to the presence of cardiac artefacts that interfered with aDBS. The group analysis ($n = 12$) among stimulation conditions (NoStim0, NoStim1, cDBS and aDBS) did not reach significance [condition: $F(3,33) = 2.27$; $p = 0.097$]. Pairwise comparisons between conditions showed a mild but significant mean low-frequency power suppression during cDBS, compared to NoStim0 (Fig. 1B) [mean difference: -0.39 ± 0.17 a.u.; $t(11) = -2.2282$; $p = 0.0477$]. The rest of the pairwise comparisons were not significant (Fig. 1C–D, Supplementary Table 1). All patients tolerated aDBS at similar voltages used for cDBS. The total amount of stimulation during aDBS was $43.05 \pm 16.8\%$ of that during cDBS. No acute changes in BFMDRS and TWSTRS scores were observed among conditions (Supplementary Table 2–4) [BFMDRS-condition $F(2,8) = 2.25$; $p = 0.1678$; TWSTRS-condition $F(2,6) = 1$; $p = 0.421$], and pairwise comparisons were not significant.

Mean low-frequency power in patients with chronic DBS ($5.73 \times 10^{-4} \pm 9.24 \times 10^{-5}$ z-scores) was significantly lower to that of DBS-naïve patients ($9.03 \times 10^{-4} \pm 9.24 \times 10^{-5}$ z-scores, Fig. 1D) [$t(22) = 2.4635$, $p = 0.0221$].

4. Discussion

In this study, we explored the effects of delivering stimulation at three different timescales in dystonia patients. Firstly, we observed that aDBS based on LFO-bursts did not lead to an acute change in either LFO-power or dystonic symptoms. Given the delayed response of dystonia to stimulation [1], it is possible that fast LFO-components are not able to directly reflect the clinical dystonic state. However, the long-term effects of targeting LFO-bursts still need to be explored. Secondly, we tested the acute effects of cDBS on LFO-power and dystonic symptoms. We confirmed that cDBS can swiftly suppress aberrant GPI-LFO [7]. This

Table 1
Clinical details of patients with dystonia included in this pilot study.

Pt.	Age	Sex	Dystonia type	Disease duration (y)	Years with DBS ^a	Type of operation	Antidystonic Medication	BFMDRS PRE/ POST ^b	TWSTRS PRE/ POST ^b	DBS parameters ^c	Channels used for recording
Adaptive Deep Brain Stimulation patients											
Dys aDBS-GPi 1	65	F	Blepharospasm and oromandibular dystonia (Meige's syndrome)	9	5	Battery replacement	Botulinum toxin every 10 weeks	22/13.5	14/9	L: 0-/C+; 1.5 V; 80 Hz; 300 µs R: -3/C+; 2.0 V; 60 Hz; 80 µs	L: 0-2 R: 1-3
Dys aDBS-GPi 2 ^d	64	M	Segmental dystonia + Parkinson's disease	4	0	New implantation	Botulinum toxin every 2 months	8/5	19/18	L: 0-/C+; 3.5 V; 135 Hz; 90 µs R: -2/C+; 3.5 V; 135 Hz; 90 µs	L: 1-3 R: 1-3
Dys aDBS-GPi 3 ^e	55	M	Segmental dystonia (torticollis)	5	2	Battery replacement	Clonazepam	23/14.25		L: -0/C+; 3.8 V; 135 Hz; 90 µs R: -0/C+; 3.7 V; 135 Hz; 90 µs	L: 0-2 R: 0-2
Dys aDBS-GPi 4	69	F	Blepharospasm and oromandibular dystonia (Meige's syndrome)	4	0	New implantation	Oxazepam	24/24	17/16	L: 0-/3+; 3.0 V; 135 Hz; 60 µs R: 0-/3+; 3.0 V; 135 Hz; 60 µs	L: 0-2 R: 0-2
Dys aDBS-GPi 5	83	F	Segmental dystonia (torticollis)	28	14	Battery replacement	Clonazepam, Pregabalin	9/6.5	19/16	L: -2/C+; 5.0 V; 130 Hz; 90 µs R: -2/C+; 5.0 V; 130 Hz; 90 µs	L: 1-3 R: 1-3
Dys aDBS-GPi 6	67	F	Oromandibular dystonia	9	3	Battery replacement	Clonazepam	17/18.25		L: -2/C+; 3.5 V; 130 Hz; 120 µs R: -2/C+; 3.5 V; 130 Hz; 120 µs	L: 1-3 R: 1-3
Dys aDBS-GPi 7	53	F	Generalized dystonia	25	3	Battery replacement	Oxazepam, Trihexyphenidyl, Botulinum toxin	63.75/44.75		L: -0/1+; 4.0 V; 130 Hz; 120 µs R: -0/1+; 3.5 V; 130 Hz; 120 µs	L: 1-3 R: 0-2
Previous cohort dystonia patients											
Dys- GPI 1	47	M	Generalized (secondary) + spastic hemiparesis	11	0	New implantation	Lorazepam	49/53		L: -1/C+; 2.2 V; 135 Hz; 90 µs R: -0/C+; 2.2 V; 135 Hz; 90 µs	L: 0-2 R: 0-2
Dys-GPi 2	52	M	Segmental dystonia (torticollis)	3	0	New implantation	Clonazepam	23/14.25		L: -0/C+; 3.8 V; 135 Hz; 90 µs R: -0/C+; 3.7 V; 135 Hz; 90 µs	L: 0-2 R: 0-2
Dys- GPI 3	52	F	Segmental dystonia (Myoclonus-dystonia)	33	0	New implantation	Propranolol, zolpidem	25.25/12	22.5/17.5	L: -1/C+; 3.2 V; 130 Hz; 60 µs R: -1/C+; 3.1 V; 130 Hz; 60 µs	L: 0-2 R: 0-2
Dys- GPI 4	63	M	Cervical dystonia	20	0	New implantation	Clonazepam	19.5/11.25	16.5/13.5	L: -0/1+; 3.6 V; 130 Hz; 60 µs R: -0/1+; 3.6 V; 130 Hz; 60 µs	L: 0-2 R: 0-2
Dys- GPI 5	63	M	Segmental dystonia (torticollis and oromandibular) + Holmes tremor	63	0	New implantation	Clonazepam	13.75/5	20/8.5	L: -1/C+; 3.4 V; 180 Hz; 120 µs R: -3/C+; 3.2 V; 130 Hz; 90µs	L: 0-2 R: 1-3
Dys- GPI 6	65	F	Segmental dystonia (torticollis)	12	0	New implantation	–	15.25/12	22/13	L: -0/C+; 3.2 V; 135 Hz; 90 µs R: -0/C+; 2.7 V; 135 Hz; 90 µs	L: 0-2 R: 0-2

^a Years in which patients have been treated with DBS at the moment of battery replacement. ^bPost-operative scores were obtained one year after DBS treatment. ^c Parameters used for cDBS in the clinical setting at the moment of battery replacement, or one year after implantation for patients measured during DBS-implantation. ^d This patient was included due to the presence of prominent segmental dystonia, which led to choose the internal globus pallidus as the DBS target, instead of the subthalamic nucleus. ^e This patient is the same as Dys-GPi 2.

result supports the hypothesis that DBS modulates pathological hyper-synchronization in the motor network [5]. However, this acute LFO-suppression is initially subtle and might not be followed by a direct change in symptom severity. Lastly, we observed that the LFO of patients who had been chronically treated with cDBS were considerably lower than those of DBS-naïve patients, even when stimulation was suspended. From all the patients treated with chronic cDBS, most of them (4/5) presented more than the minimal clinically important improvement in dystonic symptoms [11] one year after DBS implantation. Since LFO are correlated with the severity of dystonic symptoms [4], it is possible that the LFO-suppression that takes place during cDBS occurs in a gradual manner, parallel to the gradual reduction in dystonic symptoms observed after cDBS is switched on.

The re-emergence of LFO after cDBS is suspended also occurs in a gradual manner [8]. Barow et al. showed that LFO remain suppressed shortly after stimulation is applied [7]. In our study, we observed that the OFF LFO-power of patients measured after pseudo-randomization (NoStim1) was slightly lower than before pseudo-randomization (NoStim0, Fig. 1C). This can be explained by the fact that in some patients the cDBS condition preceded the NoStim1 condition. This poststimulation effect becomes more apparent when chronic stimulation is suspended, since the LFO of dystonia patients increase only gradually over a period of several hours, if symptoms increase accordingly [8]. Therefore, stimulation algorithms designed to track gradual changes in oscillatory power [12] can be tested in aDBS for dystonia (Supplementary Figure 2).

4.1. Limitations

The results obtained are preliminary, since a small patient sample was included, and only the acute effects of aDBS were explored. Similar to other studies involving LFP-recordings in dystonia, the patient group included is heterogeneous. Nevertheless, dystonic symptoms and prominent LFO were present in all patients. Prospective studies are required to explore the chronic within-subjects effect of both cDBS and aDBS on LFO and dystonic symptoms, in order to corroborate the claims provided here. However, the results obtained in this study are useful to generate data-driven hypotheses regarding the configuration of future aDBS systems for dystonia.

5. Conclusion

LFO-suppression in dystonia, similar to symptom response to cDBS, might be gradual, and remain after stimulation is suspended. Therefore, tracking gradual changes in LFO may be required for aDBS implementation. Future sensing aDBS devices will allow to explore the temporal relation between chronic LFO-suppression and dystonic symptoms [12].

Authors' roles

DPF: 1ABC, 2AB, 3A; MB: 1ABC, 2AC, 3B; JCVZ: 1C, 3B; MEvE: 1C, 3B; DLMO: 1BCE, 3A; JMCvD: 1ABC, 3B; MAJT: 1ABC, 3B.

- 1) Research project: A. Conception, B. Organization, C. Execution;
- 2) Statistical Analysis: A. Design, B. Execution, C. Review and Critique;
- 3) Manuscript: A. Writing of the first draft, B. Review and Critique.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.parkreldis.2020.08.030>.

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